sing opto-couplers

An investigation of the noise characteristics of opto-couplers used with bipolar drivers

by K. F. Knott, B.Eng., Ph.D., M.I.E.E., *University of Salford*

One of the newer devices at present becoming available in i.c. form is the optically-coupled isolator, sometimes referred to as the solid-state relay. In this device a gallium arsenide light-emitting diode (l.e.d.) and a silicon photo-transistor are adjacent on the same chip. The light from the forward-biased l.e.d. is detected by the collector-base diode of the photo-transistor and causes current flow between the collector and emitter. By modulating the l.e.d. current it is possible to transfer a signal from the l.e.d. circuit to the photo-transistor circuit. Basically the device is a unilateral current amplifier, with incremental current gain typically in the range 0.1 to 1.5 for commercially available devices. Since the coupling between input and output is optical there is very good electrical isolation between them. Isolation to d.c. may be of the order of 1 to 5kV, and the stray capacitance between input and output may be 1pF or less.

In some applications the inherent noise of the device is unimportant; however there are some applications where one requires to know the noise behaviour so that an optimum performance can be obtained. Examples of such applications are: the elimination of ground loop signals from sensitive measuring systems, where the connection of more than one mains operated instrument completes a ground loop in which interference signals can be induced; the protection of patients from the danger of electric shock due to faulty grounding of patient monitoring systems; the extraction of small signals from circuits at a high d.c. potential (for example, one may be interested in the fluctuations of current flow to an electrode which requires a large accelerating voltage). The ultimate sensitivity in such applications is set by the inherent noise of the opto-coupler. This article describes the results of an investigation of the noise behaviour of 15 samples of opto-couplers obtained from three different manufacturers (type numbers CNY43, TIS111, MCT2).

Equivalent noise circuit

Preliminary measurements showed that the output noise current of the device was independent of the input termination. Therefore, the simplest equivalent circuit for the noise has one noise current source located at the output terminals as shown in Fig. 1. The symbols in Fig 1 are:

I_D = l.e.d. bias current
r_d = l.e.d. dynamic resistance
i = small signal input current
A_i = small signal current gain
I_{CEO} = photo-transistor direct collector current
i_n = short circuit output noise current
i_0 = short circuit output current

The noise factor of the circuit is found as follows:

$$F = \frac{\text{total mean square output noise current}}{\text{mean square output noise current due to } R_S}.$$

The narrowband value of F is found if the spectral density of i_n is used in the equation rather than the mean square value. The spectral density of i_0 due to R_S is:

$$\left.\frac{\overline{i_0{}^2}}{\Delta f}\right]_{R_S} = \frac{4kTR_S}{(R_S+r_d)^2}A_i{}^2$$

$$\therefore F = 1+\frac{(\overline{i_n{}^2}/\Delta f)(R_S+r_d)^2}{4kTR_SA_i{}^2},$$

where $\overline{i_n{}^2}/\Delta f$ = spectral density of i_n at frequency f. By differentiating this equation with respect to R_S one finds that F is minimum when

$$R_{S_{(opt)}} = r_d$$

which gives,

$$F_{opt} = 1+\left(\frac{i_n}{A_i}\right)^2\frac{r_d}{kT}$$

where i_n = noise current in $\mathrm{A}/\sqrt{\mathrm{Hz}}$.
If it is assumed that the diode obeys the exponential law one may write,

$$r_d = \frac{kT}{q}\frac{1}{I_D}$$

$$\therefore F_{opt} = 1+\left(\frac{i_n}{A_i}\right)^2\frac{1}{qI_D} \qquad (1)$$

(q = electronic charge = 1.6×10^{-19}C).

It is seen from equation (1) that the noise performance of the device will depend on how $\left(\frac{i_n}{A_i}\right)^2$ varies with I_D.

Experimental results—opto-coupler

Values of i_n, A_i and also cut-off frequency, f_B, were measured for 15 samples of devices obtained from three manufacturers. Complete noise spectra were taken for each sample over the range 10Hz–100kHz. In order to minimize the effects of collector-base feedback capacitance the cascode test

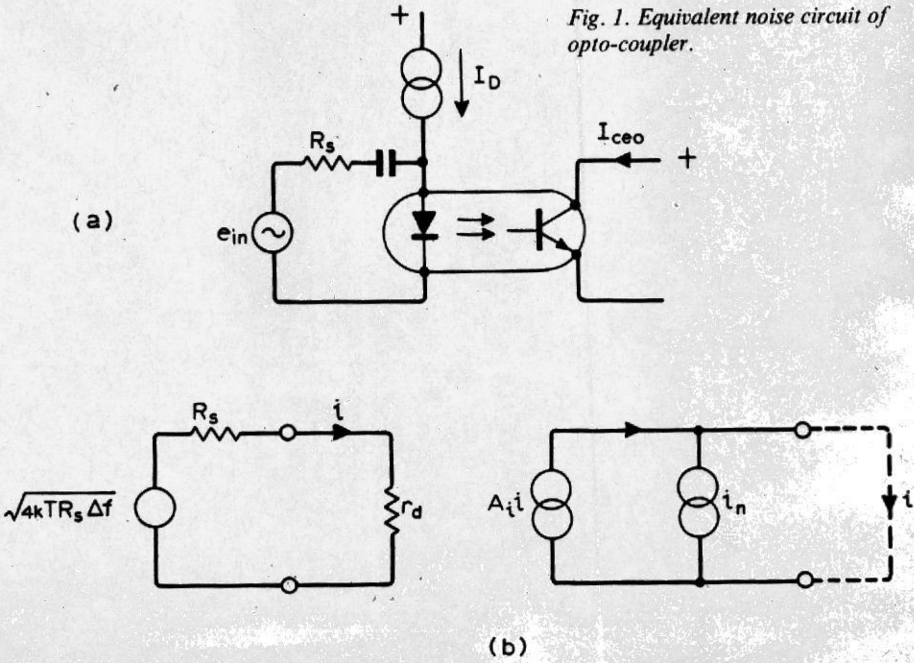

Fig. 1. Equivalent noise circuit of opto-coupler.

circuit of Fig. 2 was used. This test circuit is also useful as a post-amplifier.

In general there were no great differences between the three types of device tested so for clarity's sake the results are presented for one low-noise and one high-noise sample irrespective of type number.

The spectra of these two samples are shown in Figs. 3 and 4, with I_D as a parameter. Fig. 5 gives the variation of A_i and f_B with current for the two samples, and Figs. 6 and 7 show $\left(\frac{i_n}{A_i}\right)^2 \frac{1}{I_D}$ as a function of I_D at spot frequencies of 100Hz and 1kHz respectively. If the minimum value of F_{opt} at 1kHz is calculated for the lower noise device according to equation (1) a value of 38dB is obtained corresponding to $I_D = 500\mu A$, $R_{S(opt)} = 50\Omega$ and $f_B = 40kHz$. This device on its own therefore has a very high noise factor and also has the disadvantage of a low value of optimum source resistance. Obviously power gain is required preceding an opto-coupler if a reasonable noise performance is to be obtained.

Transistor—opto-coupler

Theory. The simplest circuit one can devise is that shown in Fig. 8(a) where the l.e.d. of the coupler is inserted directly in the collector of a common-emitter stage so that the transistor collector current is equal to the diode current I_D. In Fig. 8(b) the noise generators of the bipolar transistor and the opto-coupler have been included. By considering the various contributions to the output noise current one arrives at the expression for overall noise factor given below,

$$F = F_{bip} + \left(\frac{i_n}{A_i}\right)^2 \frac{r_e^2}{4kT\lambda R_S}$$

where r_e = incremental emitter resistance of bipolar transistor,

$$\lambda = \left(\frac{\beta r_e}{\beta r_e + R_S}\right)^2$$

(β = common-emitter current gain of bipolar transistor, F_{bip} = spot noise factor of bipolar transistor stage.)

Now, since the diode and bipolar transistor currents are equal,

$$r_e = r_d = \frac{kT}{q}\frac{1}{I_D}$$

$$\therefore F = F_{bip} + \left(\frac{i_n}{A_i}\right)^2 \cdot \frac{1}{qI_D} \cdot \frac{r_e}{4\lambda R_S}. \qquad (2)$$

If a low-noise transistor is used one can make an initial simplifying assumption that the transistor is noise-free compared with the coupler even when the power gain is taken into account. In this instance R_S coincides with the value for maximum power transfer i.e. $R_S = \beta r_e$ and $\lambda = \frac{1}{4}$. The second term on the right hand side of equation (2) then is equal to

$$\left(\frac{i_n}{A_i}\right)^2 \frac{1}{\beta q I_D}.$$

The optimum noise factor then occurs at the same value of I_D as in the previous case.

To test the validity of the assumption that the transistor is virtually noise free, suppose

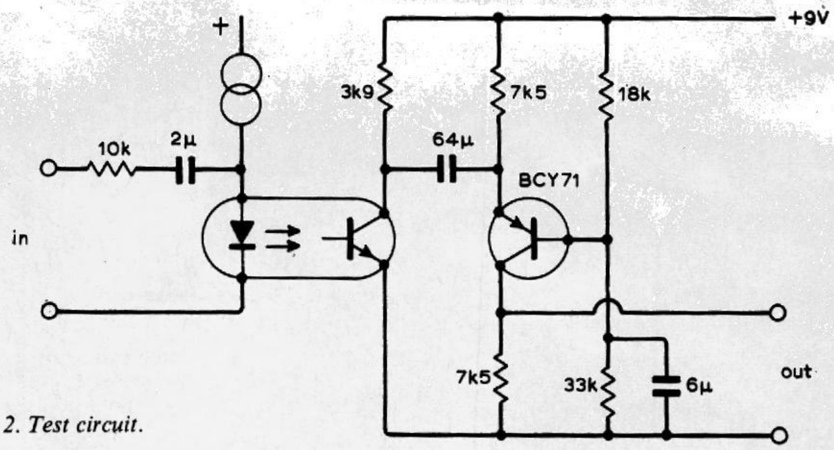

Fig. 2. Test circuit.

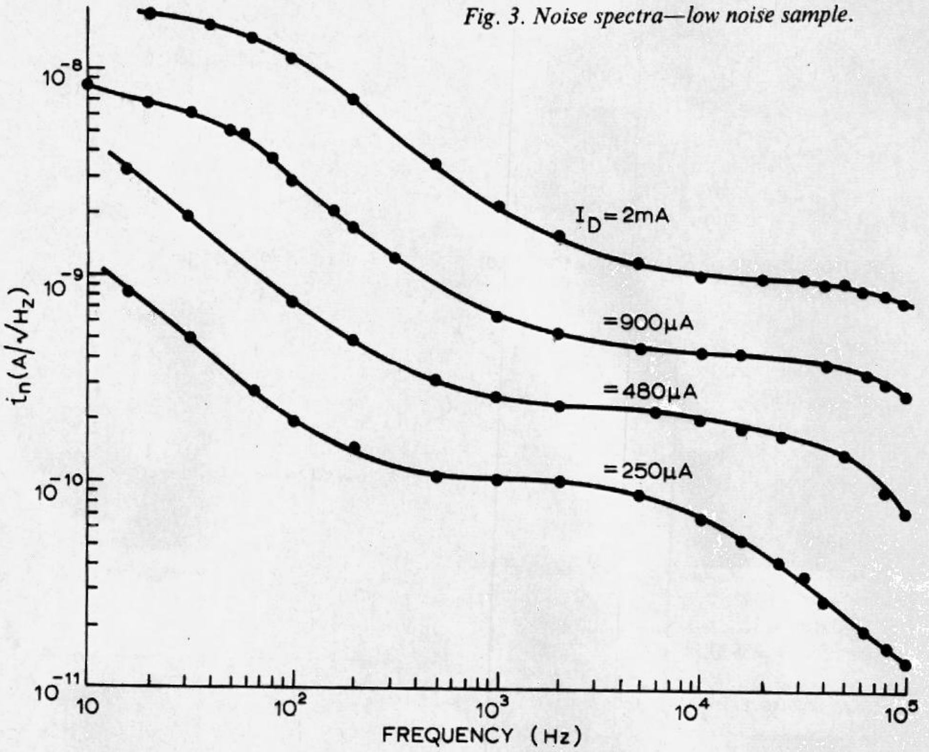

Fig. 3. Noise spectra—low noise sample.

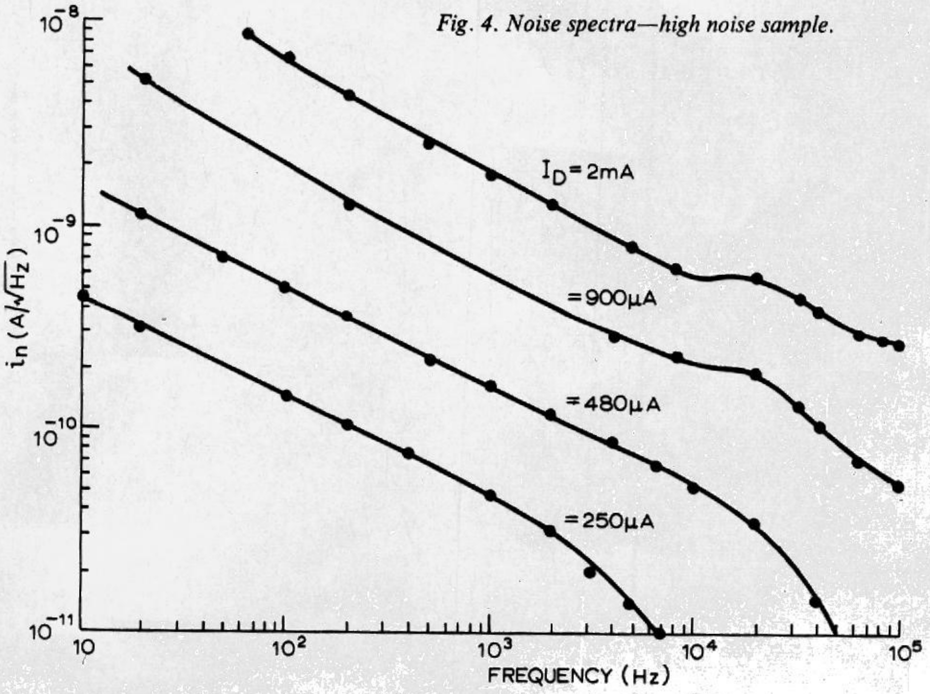

Fig. 4. Noise spectra—high noise sample.

a sample calculation is carried out at 1kHz for the lower-noise sample of opto-coupler using the following values,

$$\beta = 500$$

$$I_D = 500\mu\text{A}$$

$$\left(\frac{i_n}{A_i}\right)^2 \frac{1}{qI_D} = 6.25\times10^3.$$

If it is assumed that the bipolar transistor is free of $1/f$ noise at 1kHz,

$$F_{bip} = 1+\frac{(r_e/2)+r_{bb'}}{R_S}+\frac{R_S}{2\beta r_e},$$

where $r_{bb'}$ is the base spreading resistance. Since R_S has been chosen equal to βr_e,

$$F_{bip} = 1+\tfrac{1}{2}+\frac{1}{2\beta}+\frac{r_{bb'}}{\beta r_e}.$$

The last two terms in this equation will usually be much less than one,

$$\therefore F_{bip} \approx 1.5.$$

The overall value of F will therefore be,

$$F = 1.5+\frac{6{\cdot}25\times10^3}{500} = 14 \text{ or } 11.5\text{dB}.$$

The overall value of F, excluding transistor noise, will be:

$$F = 1.0+\frac{6.25\times10^3}{500} = 13.5 \text{ or } 11.3\text{dB}.$$

Optimum noise factor calculations. The optimum noise factor is given by

$$F_{opt} = 1+\frac{1}{\beta}\cdot\left(\frac{i_n}{A_i}\right)^2\cdot\frac{1}{qI_D} \qquad (3)$$

Use of Figs. 6 and 7 and equation (3) allows F_{opt} to be calculated as a function of I_D for various values of β at spot frequencies of 100Hz and 1kHz. Figure 9 shows sample results for $\beta = 500$.

Results—opto-coupler plus bipolar

The circuit of Fig. 8(a) was constructed using an unselected BC169 bipolar transistor in the common-emitter stage. The overall noise factor at $f = 1$kHz and $I_D = 480\mu$A was measured as a function of R_S using the lower noise sample of opto-coupler. The results are shown in Fig. 10. It is seen that the optimum source resistance is equal to βr_e but a 4:1 range of R_S could be tolerated for only a 1dB change in F. Alternatively, a 4:1 range in β could be tolerated.

The value of F_{opt} corresponding to $R_S = \beta r_e$ was then measured as a function of I_D. The results are shown in Fig. 11. Also shown on Fig. 11 is the curve calculated using equation (3) and the measured values of β. There is good agreement between the measured and calculated values of F_{opt}.

The good agreement between experimental and theoretical results justifies the simplifying assumptions made in the theory. The noise performance of both the high noise and low noise samples will be nearly optimum at a diode current of 500μA, but one must bear in mind the reduced bandwidth and current transfer ratio at this current when designing any particular system. The combination of a bipolar stage and a low-raise opto-coupler has a noise factor low enough to use as a second stage and perhaps even low enough to use as a first stage. However, the combination of a bipolar stage and the high noise sample of opto-coupler would have to be preceded by a stage of power gain in order to obtain a low overall noise factor.

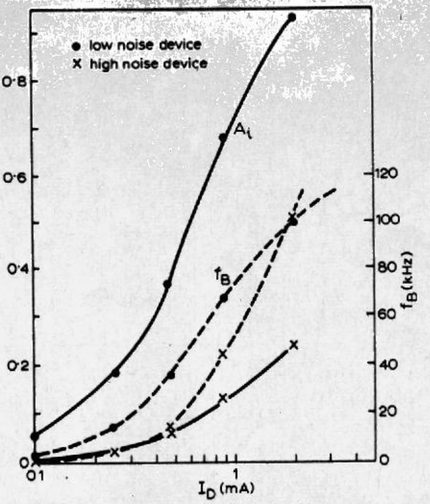

Fig. 5. Current gain and bandwidth as a function of I_D.

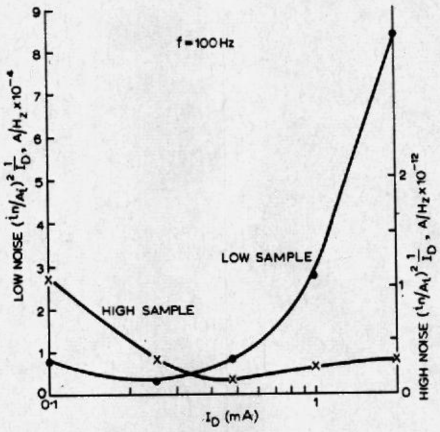

Fig. 6. $\left(\frac{i_n}{A_i}\right)^2\frac{1}{I_D}$ *as a function of I_D,*
$f = 100$Hz.

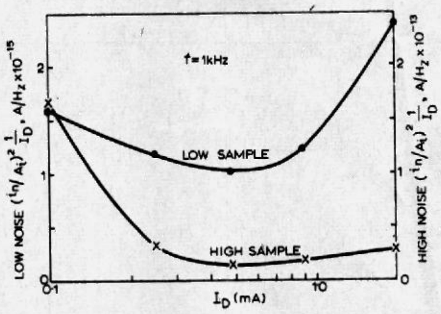

Fig. 7. $\left(\frac{i_n}{A_i}\right)^2\frac{1}{I_D}$ *as a function of I_D,*
$f = 1$kHz.

A conservative worst case design using the high noise sample with a bipolar having a range in β of 150–600 would be:

$$\text{Set } R_S = 16\text{k}\Omega$$

$$I_D = 500\mu\text{A}.$$

Precede this combination with a further low-noise bipolar stage having an available power gain of 30dB.

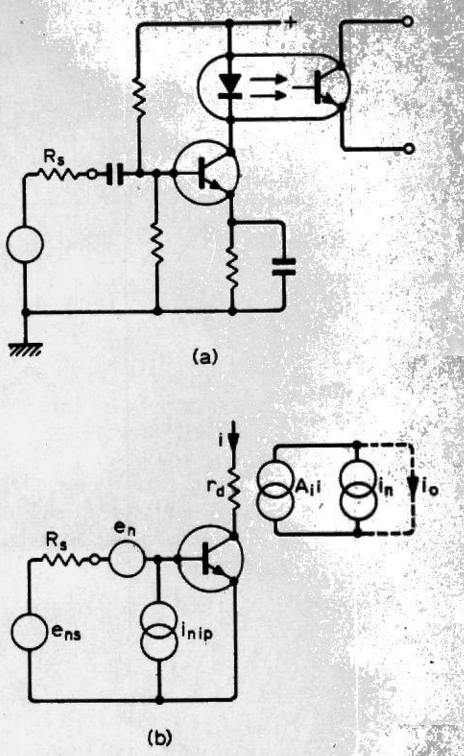

Fig. 8. Transistor-opto-coupler combination.

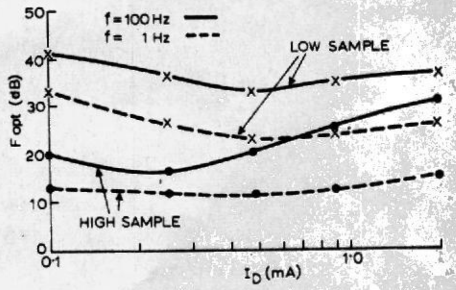

Fig. 9. Calculated F_{opt} assuming noise free bipolar stage.

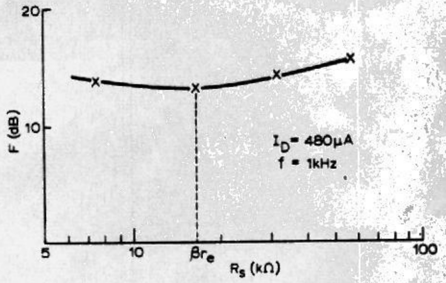

Fig. 10. F as a function of R_S for an actual circuit.

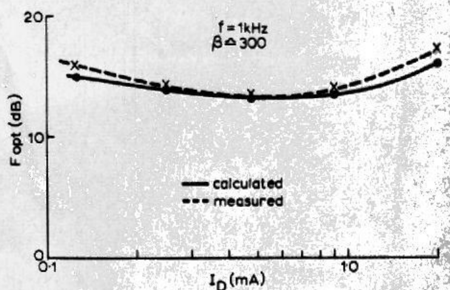

Fig. 11. Measured and calculated F_{opt} as a function of I_D for an actual circuit.